Steady-state natural circulation analysis with computational fluid dynamic codes of a liquid metal-cooled accelerator driven system

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ABSTRACT

A new innovative nuclear installation is under research in the nuclear community for its potential application to nuclear waste management and, above all, for its capability to enhance the sustainability of nuclear energy in the future as component of a new nuclear fuel cycle in which its efficiency in terms of primary Uranium ore profit and radioactive waste generation will be improved. Such new nuclear installations are called accelerator driven system (ADS) and are the result of a profitable symbiosis between accelerator technology, high-energy physics and reactor technology. Many ADS concepts are based on the utilization of heavy liquid metal (HLM) coolants due to its neutronic and thermo-physical properties. Moreover, such coolants permit the operation in free circulation mode, one of the main aims of passive systems. In this paper, such operation regime is analysed in a proposed ADS design applying computational fluid dynamics (CFD).

1. Introduction

The energy supply to humankind is one of the most critical issues that our Society has to take care to keep our social, economic and human development. This energy supply, on the other hand, should keep our available natural resources and be friendly with the environment, what implies the need to develop and put into practice energy technologies that should be sustainable in the medium-long term.

Nuclear energy is one of the available technologies that are envisaged to be taken into consideration in future energy markets due to its mature technology, its availability and its negligible global warning gases emission. Nevertheless, some improvements should be done for its overall sustainability, in particular in relation with radioactive waste management and fuel cycle efficiency.

Partitioning and transmutation (P&T) is a research activity in which international and national efforts are devoted to the development of new techniques to reduce the inventory and radioactive hazard of the nuclear wastes produced in the exploitation of nuclear energy (Martinez-Val and Piera, 2007). Briefly, P&T seeks a clean nuclear fuel cycle producing a waste stream with a negligible content of transuranics and long lived fission products by the development of suitable nuclear reactors (either critical or subcritical) and separation technologies (Salvatores, 2005).

One of the most promising reactor types that are being considered for transmutation of nuclear waste is an accelerator driven system (ADS). This kind of nuclear installation is composed basically by an accelerator, a high intensity neutron source and a subcritical reactor (Bowman et al., 1992; Rubbia et al., 1995). Many of this concepts has been proposed and some of them are under study at different development stage in many countries, and very ambitious programs are running as is the case of the accelerator transmutation of wastes (ATW) and derivatives in United States (ATW Roadmap, 1995), the IP-EUROTRANS in Europe, and other initiatives in Japan (Sasa et al., 2004), South Korea (Park et al., 2002), China or India, and some activities are running under the umbrella of international organizations as the IAEA (Stanculescu, 2006) and the NEA/OECD.

The technological challenges for the development of accelerator driven systems are miscellaneous due to the integration of accelerator technology, high-energy physics phenomena and subcritical reactor technology, including new required developments for fuel fabrication and isotope partitioning.

One of the key technical aspects is the utilization of a liquid metal as Lead, or eutectic Lead/Bismuth (LBE) as one of the main material component of an ADS. These heavy liquid metals have very interesting nuclear and thermo-physical properties, what makes them the preferred material selection as coolant and neutron generation target in most of the proposed concepts.

The thermal-hydraulic analysis of Lead- or LBE-cooled ADS has been addressed using different approaches. The core analysis has been mainly done by the modification of nuclear thermal-hydraulic codes, as RELAP (Bandini et al., 2006) or TRAC (Ma et al., 2006) to their application to heavy liquid metal phenomena. These codes use a proper nodalization with different details, including some neutronic features. Another approach is the application of CFD codes (Tucek et al., 2006), what make possible a very detailed geometrical modelisation where main conservation law equations are solved. Some analysis has been done coupling the computational fluid dynamic code with a neutronic module in the framework of the IP-EUROTRANS project, although, under our point of view, the large amount of computational resources for a detailed description of the reactor core makes very tough to obtain results that could compete in terms of accuracy and computational cost with modularised and phenomenological codes as RELAP or TRAC.

The aim of this paper is the study of the passive behaviour during normal operation of a proposed Lead-cooled ADS design (ANSALDO, 1999) which main cooling mechanism is free convection. For that purpose, a 2D axisymmetric representation of that ADS design has been set-up using the computational fluid dynamic (CFD) FLUENT code (FLUENT, 2005). The model includes the core, a riser cylinder and a heat exchanger in the upper part of the downcomer, as well as a gas plenum on top of the fluid. The vessel, the safety vessel around this one, and the reactor vessel air coolant system (RVACS) are also modelled, what has not been considered in previous works (Ceballos, 2007).

2. Heavy liquid metals in nuclear applications

The nuclear properties of the referred heavy liquid metals (Pb and eutectic Pb/Bi) are very adequate for transmutation of nuclear wastes as their heavy nuclei make possible to obtain a very fast neutron spectrum if they are used as neutron diffusion medium. The small energy loss at each neutron scattering in such heavy nuclei might lead to the application of the adiabatic resonance moderation scheme (Abánades et al., 2001), in which neutrons are able to pass thought the full energy range from their generation by fission to its capture at thermal energies. Moreover, heavy nuclei are neutron rich, with a very high ratio between neutrons and protons. This means that any spallation process will produce a high amount of neutrons, being the reason for its application as hadron induced neutron generation target material. The efficiency of the neutron production in a Lead or eutectic Lead/Bismuth target will be also favoured by its small capture to scattering cross-section ratio.

Liquid metals are materials with high thermal conductivity from its metallic nature, what implies that liquid metals have large thermal diffusivities. This is very suitable for cooling purposes and it is one of the reasons for the use of liquid metals in applications with high-energy power densities and heat transfer fluxes, as it is the case of some nuclear devices. The good coolant properties of liquid metals are enhanced by its high volumetric expansion coefficient, what leads to applications with high Grashoff number in which natural convection can play an important role. Free convection is a very important cooling mode because it permits a passive design, that is an appreciated feature from the point of view of the safety as ensure coolability even under abnormal operation.

The Prandtl number relates the dynamic viscosity of the fluid and its thermal conductivity. Low Prandtl number implies that turbulent effects have relatively less importance than heat conduction in the flow if compared with more used coolants as water or air. Low Prandtl number fluids are characterized by their difficulty to develop turbulence by its relative high dynamic viscosity, what burden heat transfer by momentum exchange, making more relevant than usual heat transfer by molecular conduction, given a flow pattern in which temperature gradients may be important, or at least more relevant than with other common coolants as water. This is also a consequence of its low Peclet number.

The main consequence in the hydrodynamic modelling is that thermal and velocity boundary layers are very different between liquid metals and other coolants as water or air, and the Reynolds analogy (applicable when $\mathrm{Pr}_t \tilde{1}$ and used by most of available turbulence models) becomes inadequate. Concerning free convection application, the low Prandtl number implies a low Rayleigh number, what means that heavy liquid metals free convection flow has a tendency to stay laminar.

The high boiling point of heavy liquid metals and their material compatibility with air, steam, carbon dioxide and water makes them a good choice as coolant for power engineering devices, and nuclear installations in particular, in opposition to soft liquid metals as Sodium. In the case of eutectic Lead/Bismuth, the low melting point (125 °C) makes this liquid metal the preferred option as coolants for ADS design in comparison with Lead (325 °C) due to its lower solidification risk, but has the drawback of the alpha radioactivity production due to Polonium accumulation by neutron capture when used as nuclear coolant.

3. Buoyancy forces in heavy liquid metals applied to free convection cooling

One of the main advantages of ADS is their inherent safety due to their operation in subcritical mode. The neutronic behaviour of a subcritical system is fairly favourable respect to a critical system, mainly in terms of response to any reactivity insertion (Rief and Wider, 1999). In particular, this feature is especially interesting in the case of fast reactors where safety in terms of prompt criticality margins (due to a lower fraction of delay neutrons in the fuel) is narrower than in commercial thermal water reactors. This subcritical operation mode is also interesting from the point of view of fuel flexibility and efficiency, making possible a higher burn-up due to the fact that the material inventory in the core do not need to stay supercritical.

Apart from their neutronic inherent safety, natural convection pumping has been considered in Lead or eutectic Lead/Bismuth for many ADS proposals, in particular in the energy amplifier (Rubbia et al., 1995), to have a full passive nuclear device, what it is of high interest for any nuclear installation.

Briefly, the pressure difference generated in the cooling loop of a pool reactor by coolant temperature difference is given by the expression:

$$\Delta P = K \cdot h \cdot g \cdot \Delta T \tag{1}$$

where T is the temperature difference between the hot and cold leg (in a first approximation the temperature increase of the coolant in the core); K is the coolant thermal expansion coefficient (in Lead 1.32 kg m^{-3} K^{-1}); h is the height of the liquid column; and g the gravity. The pressure losses depend on the cooling loop design and the velocity profiles that will be imposed by natural convection. In addition, pressure losses depend upon mass flow rates that are given by the core thermal power, the coolant heat capacity and temperature increase. Every of theses effects are coupled to fix a steady-state operation mode with a certain coolant mass flow rate and temperature increase for a given core power.

In the case of the Rubbia's proposal, the Lead height column was 25 m for its fuel bundle design for a 1500 MWth device with a primary cooling circuit pressure loss of 0.637 bar. In the case of smaller ADS devices based on natural convection, as the one proposed by the LAESA company at the end of the 1990s, the required Lead height was 8 m for a 250 MWth device (Abánades and Pérez-Navarro, 2000).

A free convection fluid motion enhancement can be obtained by gas injection in the hot leg of the liquid metal circuit as proposed by the energy amplifier demonstration facility (Ambrosini et al., 2005). The gas injection decreases the density of the hot leg fluid, increasing the effective thermal expansion coefficient in the previous expression, referred now to a biphasic bubbly flow. The result is

Table 1
Main parameters of the energy amplifier demonstration facility.

Parameter	Value	Unit
Primary coolant flow	5836	kg/s
Core coolant flow	5345	kg/s
Core pressure loss	20	kPa
Total pressure loss in primary loop	29	kPa
Argon injection flow rate (when active)	100	0.1 m^2/s
Core material	AISI 316 L	
Core Power	80	MW
Primary coolant	Eutectic Lead/Bismuth	
Inlet/Outlet coolant temperature	300/400	°C

the decrease of the liquid column height for a given core power, and a reduction in the volume of the whole pool reactor and, therefore, its cost in terms of structural materials and coolant mass.

4. Description of the energy amplifier demonstration facility (EADF)

The energy amplifier demonstration facility has the layout shown in Fig. 1. All the pictures that are attached are from the ANSALDO reference design (ANSALDO, 1999). The main components of this ADS design are the following:

- Proton accelerator: provides a high-energy proton beam in order to collide on a high-Z target for generating the neutron source for the spallation reactions. The deposited power of the beam in the target is between 1950 kW and 3000 kW depending on the core criticality level.
- Target Unit: The target unit (number 5 in Fig. 1) is embedded in the central part of the core of the subcritical reactor, producing the neutrons that keep the power level in the core. The high-Z material that collides with the proton beam is the Lead/Bismuth (Pb/Bi) eutectic in this case. There are two different possibilities for the target unit design. The first one is to consider a window between the target and the pipe of the proton beam; and in the second option there is a free surface of Pb/Bi directly in contact with the pipe. The power generated by the spallation reactions is 1 kW/cm^3. And the beam deposits 3% of its energy contents on the window. On the other hand, there is a target coolant circuit for the removal of the 3.0 MW produced by spallation. CFD is considered a very powerful engineering tool for the design of this specific component and has been used intensively for its design (Tak et al., 2005).
- Core: The core has an arrangement of a honeycomb (number 1 in Fig. 1), with a total amount of 120 fuel assemblies. The middle plane of the core is 5.8 m below the free surface of the Pb/Bi coolant. The nominal power is 80 MW and the average power density in the fuel is $46.73 \times 10^6\ W/m^3$. Surrounding the fuel core,

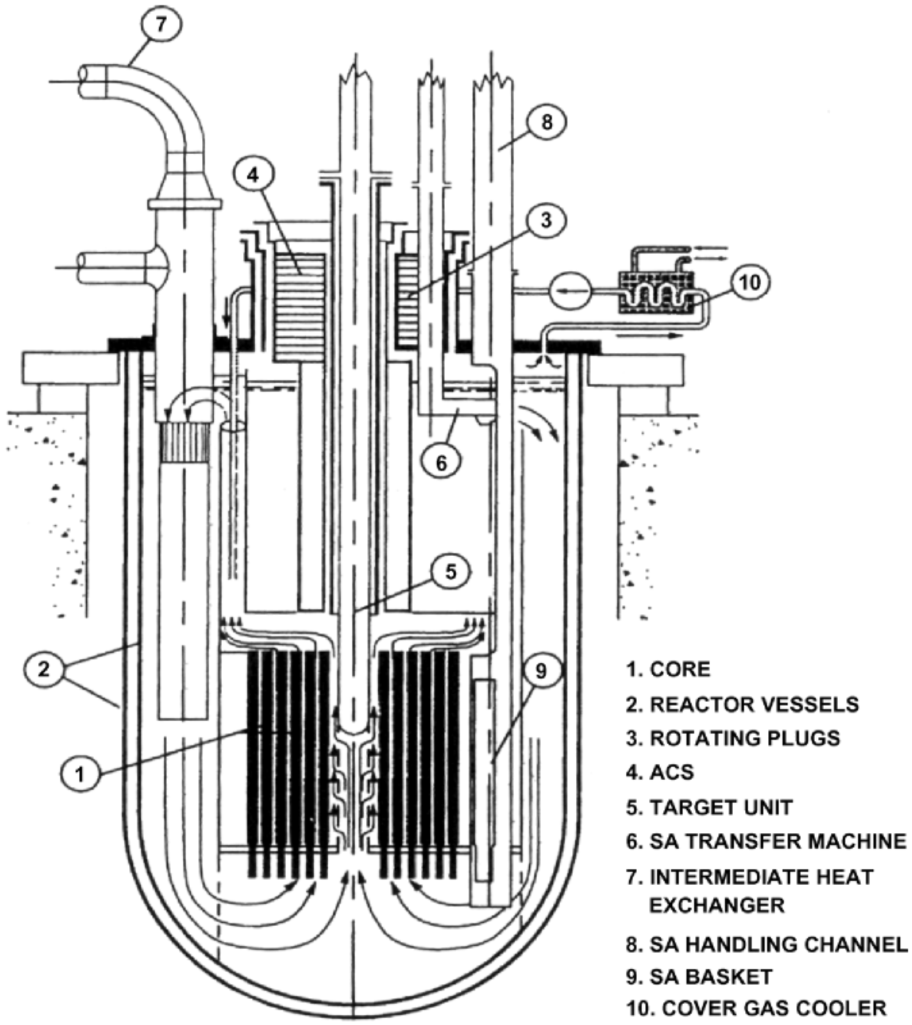

Fig. 1. Scheme of the energy amplifier demonstration facility.

there is a structure, also in a honeycomb-like distribution, including the so-called dummy assemblies containing mainly Pb/Bi. The purpose of these dummy assemblies is that they form a barrier for the neutrons coming from the core, so the internal structures are being protected from serious radiation damage. Another reason for these dummy assemblies is that there is also the possibility of inserting test assemblies. The main thermal-hydraulic parameters of this facility are given in Table 1.

- Primary system: Pumps are not foreseen due to the possibility of free convection cooling. However, a continuous Argon gas injection could enhance flow circulation. If no injection is present, the coolant flow will be carried on by natural convection driven by density differences. The absence of pumps allows simpler display geometries, without piping and pressurised plenums.
- Reactor vessel air coolant system (RVACS): The safety-related core decay heat removal is accomplished by a passive system called RVAC. This system is basically a safety vessel between the reactor vessel and the reactor pit with the gap between these two vessels containing air. This system is configured as U-tubes with atmospheric air flowing in natural circulation. And the heat is transferred fully by natural convection from the primary coolant to the air as follows:
  - Conduction through the Reactor Vessel wall.
  - Radiation and Convection from the Reactor Vessel wall to the Safety Vessel.
  - Conduction through the Safety Vessel wall.
  - Radiation and Convection from the Safety Vessel to the tubes of the RVACS.

5. Computational fluid dynamics analysis

A finite element approach has been used in the present work for the analysis of the steady-state conditions that are reached when free convection becomes the main driven force as cooling mechanism on the proposed ADS design. Such analysis must be done assuming some simplifications to arrive to a practical simulation scheme with a reasonable compromise between computing effort and reliability of the results.

The simulation was done in a 2D axisymmetric geometry, as shown in Fig. 2 with a model of nearly 40,000 cells. The modelling

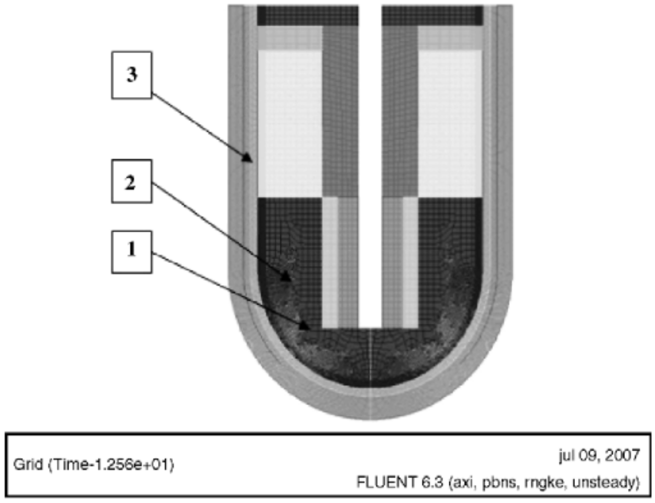

Fig. 2. Scheme of the computational grid and it porous media model for the core, the dummy assemblies and the heat exchanger.

simplifications have been focused in the heat exchanger (zone 3 in Fig. 2), the core (zone 1 in Fig. 2) and the dummy assemblies (zone 2 in Fig. 2), for which a porous media is used instead of a full geometry description. The porous media description is based on coefficients previously estimated from pressure drop evaluation at each zone taking into account the detailed geometry design at each zone.

Most of the coolant flow should pass through the core for cooling the fuel assemblies. Consequently, a very small flow area has been assumed for the dummy assemblies, in order to get the Pb/Bi passing mainly through the core. As can be seen in Table 1, the flow rates foreseen are 5345 kg/s through the core, and 491 kg/s through the dummy assemblies.

The neutron generation target is not included in our simulation as it is physically apart from the core and can be considered as an independent component of any ADS. The core power is set by the neutron source strength trough by a proportionality law that depends on the core criticality level. Moreover, subcritical operation also implies a non-homogenous power density distribution. Nevertheless, in our porous media description, we have assumed

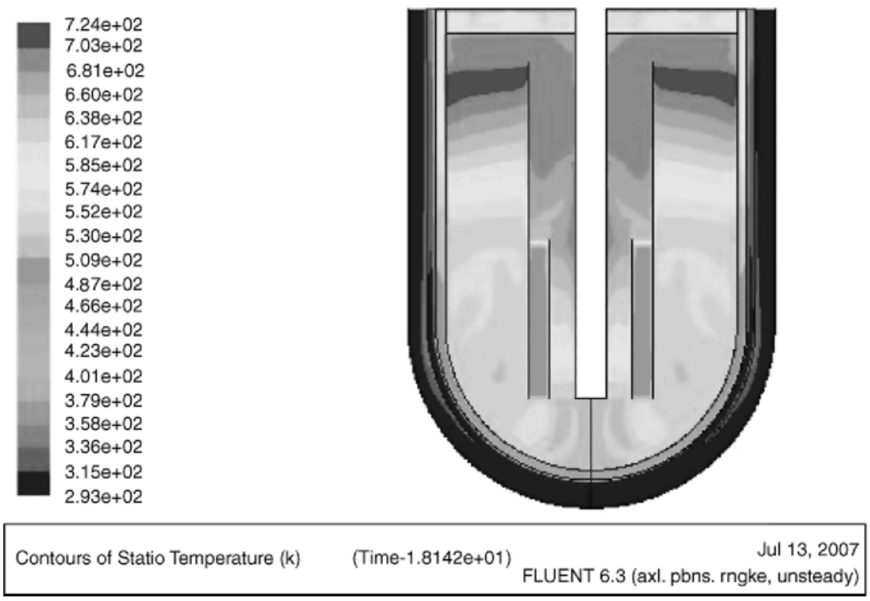

Fig. 3. Temperature contours in the energy amplifier demonstration facility for fully natural convection.

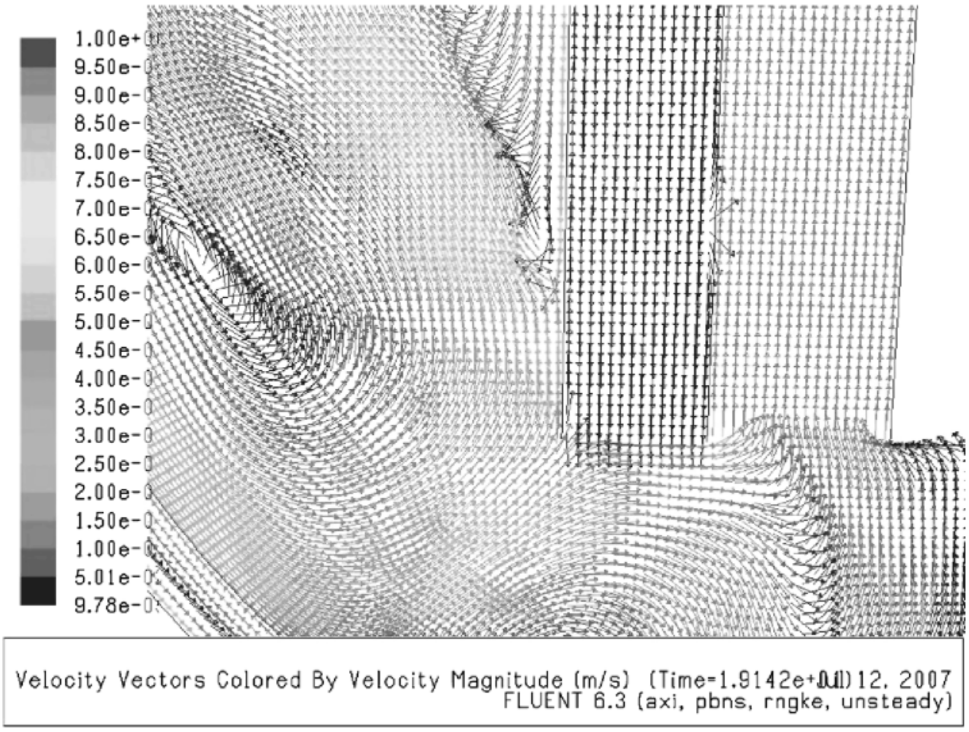

Fig. 4. Detail of the recirculation at the core inlet.

a homogenous energy source of $1.25{\cdot}10^7\,\mathrm{W/m^3}$ for the nominal 80 MWth and a core volume of $6.386\,\mathrm{m^3}$. We believe that such simplification do not affect the description of the overall behaviour of the primary loop, as the height of the coolant column is much larger than the core.

It is well known that the heat removal capability of the heat exchanger play an important role in the temperature level if the primary loop, specially in the case of transients. Nevertheless, for this steady-state simulation the heat exchanger and the secondary loop have been represented as a power sink equivalent to the power generated in the core.

We considered that free surface instabilities of the eutectic can be neglected. Therefore, we have simulated the top of the primary cooling circuit as artificially separated from the plenum by a wall, considered as a blackbody for radiation calculations with no thickness and with the slip condition at this wall surface.

For a correct simulation of the natural circulation of the Pb/Bi coolant, the Boussinesq approximation seems to be the best

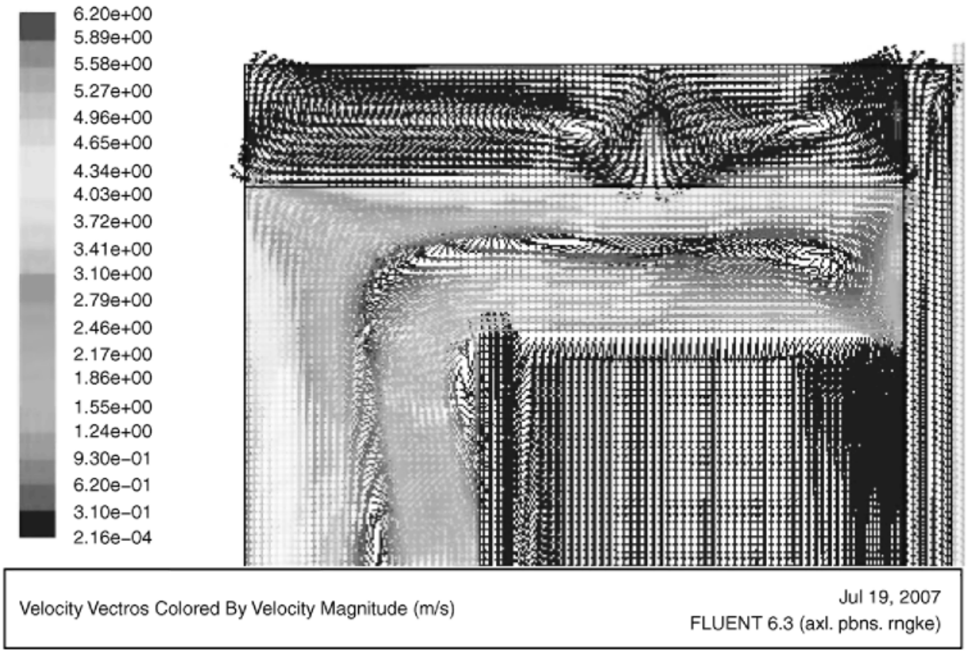

Fig. 5. Detail of the flow in the upper part of the core, at the outlet of the heat exchanger.

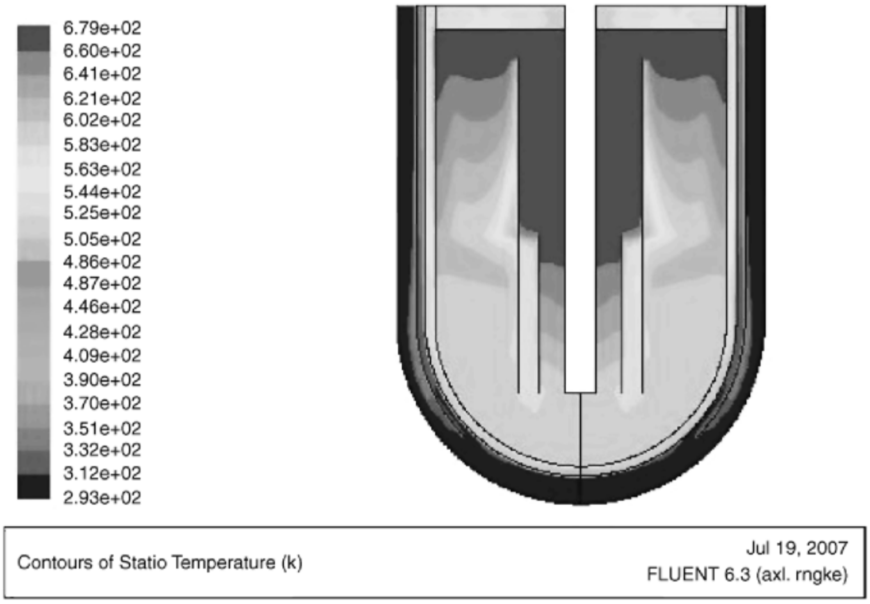

Fig. 6. Temperature distribution with free convection enhancement with Argon injection.

solution for flows involving natural convection, due to its good convergence. In this approximation, the user inputs a reference density (ρ_0) correspondent to an operating temperature (T_0) also specified by the user. And the density at each temperature is calculated with the expression:

$$\rho = \rho_0(1 - \beta(T - T_0)) \tag{2}$$

with β the thermal expansion coefficient. The model treats density as constant, except in the buoyancy term in the momentum equation.

The discrete phase model has been included in order to simulate the injection of Argon bubbles that enhance the free convection effects in the primary cooling loop. The 1-mm diameter spherical bubbles are injected 0.5 m above the core outlet, as provided by the expected gas injection system design.

For these calculations the discretization schemes are the second order UPWIND scheme for momentum and energy equations, and the second order UPWIND scheme for the turbulence equations.

Finally, k- ϵ RNG model has been used for the turbulence modelling. From our work in the framework of the ASCHLIM project (Arien, 2003), this turbulent model has appeared as more convenient for liquid metal thermalhydraulic analysis in the present state-of-the-art of commercial CFD codes. It was also included a correction term that accounts for low-Reynolds numbers.

6. Natural convection in the EADF core

In this paper, the behaviour of the energy amplifier demonstration facility is analyzed for two operational modes. In our first analysis gas injection is not considered. Therefore, the cooling of the facility is only driven by fully natural convection. The mass flow rate through the core is 2600 kg/s, far from the flow rate foreseen for normal operation (5836 kg/s) with gas injection. Anyway, Fig. 3 shows, that even without free convection enhancement by gas injection, the operation of this facility is safe, as the higher temperatures (724 K) are still below the boiling point of Lead/Bismuth eutectic (1670 °C).

The local analysis of the flow shows some recirculation of the coolant near the lower part of the vessel and in the dummy as can be seen in Fig. 4, as a consequence of the direction change at the outlet of the core that the flow should follow to reach the riser channel.

The second analysis has been made with natural convection enhancement with Argon injection as proposed by ANSALDO (Peña and Legarda, 2000) to compare with the natural circulation calculation. Gas injection is simulated through the discrete phase model included in the FLUENT code. The Argon bubbling position and diameter has been adjusted to get the coolant flow rate required in the reference design.

It could be realised in Figs. 5 and 6, the enhancement in the velocity of the coolant (maximum velocity: 6.2 m/s, compared with 1 m/s as maximum velocity in previous natural circulation without gas injection), and, therefore, the lower maximum temperature, and the lower temperature difference through the core (100 K, compared with 150 K in the case of natural circulation). Fig. 5 shows a detail at the inlet of the heat exchanger in the right side with the hot leg in the left side.

The temperature difference between the core inlet and the outlet can be depicted in Figs. 7 and 8 in function of the radial distance to the core axis. The fluid motion enhancement by 100 l/s Argon injection implies the reduction of the temperature difference of

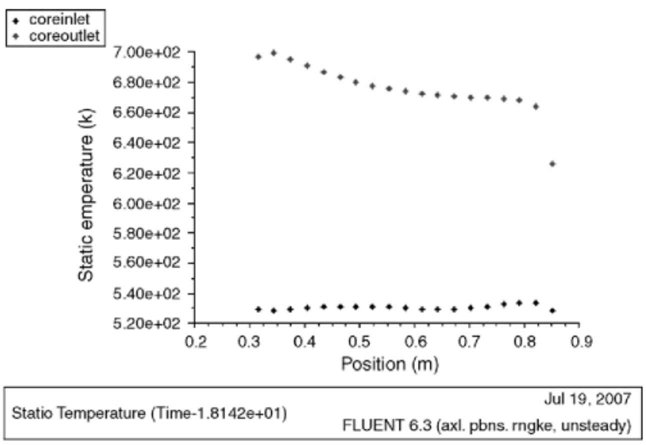

Fig. 7. Core inlet and outlet temperature with fully natural convection.

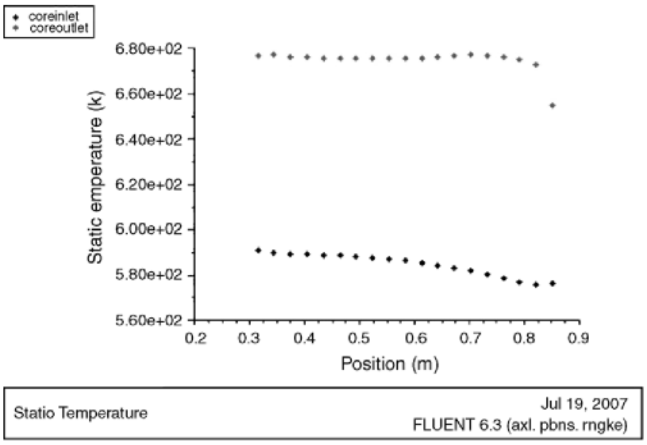

Fig. 8. Core inlet and outlet temperature with gas injection.

the coolant passing trough the core to evacuate the 80 MWth. The fluid motion enhancement implies a coolant velocity increase, what means a higher mass flow rate, and higher pressure drops that in fully free convection operation mode. Nevertheless, the Argon bubbling effect reduces the operational temperatures in the core due to the increase in the lift effect produced by density reduction of the hot leg.

7. Conclusion

Liquid metal technology is under study for its application to different new nuclear systems, as is the case of accelerator driven system, Generation IV concepts or Fusion reactors. The thermal properties of this kind of materials make them very attractive for its application as coolants. In particular, their high thermal expansion coefficients and high conductivity are of great interest for its application to free convection cooling for high power density devices, as is the case of nuclear installations and accelerator driven systems.

In this paper, the analysis of the free convection cooling mode of one of the reference ADS design has been shown, what has included many physical models to account for every phenomena that can take place in this simulation, including a two-phase model for the Argon bubbles that are used to enhance liquid metal motion. Some experimental, modelling and validation work should be done to rely on liquid metal technology CFD calculation from international experience in the field (Arien, 2003).

Nevertheless, and taking into account the uncertainties in the application of CFD modelling to liquid metal technology, we can assess that a liquid metal-cooled ADS based on Lead/Bismuth eutectic natural convection cooling will operate safely, even in the cases that gas injection mechanism to enhance fluid motion fails. Our results shows how the temperature difference for a given vessel geometry (liquid metal column height) is far from being critical from the point of view of safety. In our simulation, the temperature difference in the core doubled from 90 ◦ C to 170 ◦ C at maximum in the case of gas lifting failure, what will leads to temperatures far below the Pb/Bi eutectic boiling point (1670 ◦C), and also compatible with stainless steel 316, that can operate continuously at this temperature range (below 500 ◦), even at fully natural convection mode.

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